Model Development to Support Analysis of Acoustic Buried Target Data

Raymond Lim
NSWCPCD, Code HS-11, 110 Vernon Ave, Panama City, FL 32407
Phone: (850) 235-5178 Fax: (850) 235-5374 Email: raymond.lim@navy.mil

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LONG-TERM GOAL

The work reported here makes use of scattering models to understand and develop quantitative predictions for the sub-critical-grazing-angle target detection performance observed in sonar field tests using the Naval Surface Warfare Center Panama City Division's (NSWCPCD) synthetic aperture sonar (SAS) systems. Recent investigations have confirmed that diffraction of sound into the bottom by surface ripple can greatly enhance the detection of cylindrical targets buried as much as 50 cm in a fairly uniform sand bottom, even when the average grazing angle is low enough (e.g., below the critical grazing angle) and frequencies high enough that detection would normally be expected to be very difficult. Furthermore, evanescent waves provide a mechanism for enhanced detection of buried targets at low frequencies that little quantitative validation has been carried out for. The long-term goal is to identify the mechanism and relevant environmental parameters responsible for detection and use this information to formulate models that reliably predict sonar detection and classification/identification performance against buried mines.

OBJECTIVES

The work performed this year follows up on work begun in previous years to use buried target scattering models to predict and explain the performance of synthetic aperture sonar (SAS) for imaging targets buried in a sand bottom. Current models are configured to account for scattering by elongated targets (e.g., a finite cylinder) buried in an attenuating bottom with a rippled upper interface. A continuing objective has been to use these models to check that ripple diffraction correctly accounts for enhanced sound transmission and target backscatter at shallow sonar grazing angles by comparing their predictions with laboratory and controlled field measurements. Another objective this year has been to update the existing scattering models to account for potential curved wave front effects, which have arisen in recent data/model comparisons as a potential explanation for discrepancies generated in model predictions using recently measured bottom parameters. Wave front curvature can become important when attenuation in the bottom is low and the source is sufficiently close enough to the target. Compared to predictions with an incident plane wave, a bounded beam of sufficient width can propagate sound into the bottom to a buried target at a higher grazing angle than the beam axis angle, resulting in an enhancement of the backscatter at high frequencies. This mechanism is suspected to cause a slower decay of the first-order perturbation backscatter prediction at high frequency for a target buried under a rippled surface.

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14. ABSTRACT
The work reported here makes use of scattering models to understand and develop quantitative predictions for the sub-critical-grazing-angle target detection performance observed in sonar field tests using the Naval Surface Warfare Center Panama City Division?s (NSWCPCD) synthetic aperture sonar (SAS) systems. Recent investigations have confirmed that diffraction of sound into the bottom by surface ripple can greatly enhance the detection of cylindrical targets buried as much as 50 cm in a fairly uniform sand bottom, even when the average grazing angle is low enough (e.g., below the critical grazing angle) and frequencies high enough that detection would normally be expected to be very difficult. Furthermore, evanescent waves provide a mechanism for enhanced detection of buried targets at low frequencies that little quantitative validation has been carried out for. The long-term goal is to identify the mechanism and relevant environmental parameters responsible for detection and use this information to formulate models that reliably predict sonar detection and classification/identification performance against buried mines.

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APPROACH

As in previous years, the investigations performed used comparisons between model predictions and data collected in controlled measurements with buried targets to validate ripple scattering as a mechanism for enhancing backscatter by buried targets. For simple target shapes, the model predictions are generated from high-fidelity acoustic scattering solutions based on the transition (T) matrix method [1] to account for free-field scattering within the sediment, layered-medium basis functions to account for propagation to and from the scatterer [2], and Rayleigh-Rice perturbation theory to account for transmission across interface roughness in the basis functions [3]. For target shapes that the T matrix approach has difficulty with, PCSWAT is updated and verified against the simpler shapes accessible to the T matrix and then PCSWAT is used to compare with data collected using more complex shapes. In comparisons performed this year, spectral filters were applied to a set of controlled data from a buried spherical shell collected during the SAX04 field measurement off Panama City to enable a quantitative comparison with T-matrix predictions. Controlled data useful for model comparisons were also collected in NSWCPCD's freshwater pond facility by Applied Physics Laboratory at the University of Washington (APL-UW) and NSWCPCD with support from separate ONR projects (document #'s N0001408WX20005, N0001408WX20128, N0001408WX21015).

In order to account for curved wave front effects in model/data comparisons, far-field and incident plane-wave approximations were removed from the basis functions $\psi_n(\mathbf{r})$ and source field expansion coefficients a_n used in the transition (T)-matrix formulation of the scattered field $\Phi^{scatt}(\mathbf{r})$. These were computed in near-field regions, where the required quantities for a target buried in an environment consisting of two halfspaces are given by [2]

$$\Phi^{scatt}(\mathbf{r}) = \sum_n \psi_n(\mathbf{r})\mathbf{T}_{nn'}a_{n'}(\mathbf{r_s})\,,\ \ n=\{\sigma,m,l\}\,, \tag{1}$$

where

$$a_{\sigma ml}(\varsigma_s,\theta_s,\varphi_s) = \frac{i^{m+1}}{2\pi}\left(\frac{\varepsilon_m}{2\pi}\right)^{1/2}\int d\mathbf{q}\int d\mathbf{q}'\,\mathrm{B}_{m'l'}(-\frac{h_2(q)}{k_2})W_{12}(\mathbf{q},\mathbf{q}',\kappa)\mathrm{B}_{ml}(-\frac{h_2(q')}{k_2})$$
$$\times\frac{e^{ih_2(q)b-ih_1(q')(b-z_s)-iq'\varsigma_s\cos(\varphi_{q'}-\varphi_s)}}{h_1(q')}\begin{pmatrix}\cos m\varphi_q\,,\ \sigma=e\\ \sin m\varphi_q\,,\ \sigma=o\end{pmatrix}, \tag{2}$$

$$\mathrm{B}_{ml}(-\frac{h_2(q)}{k_2}) = i^{l-m}(\frac{2l+1}{2}\frac{(l+m)!}{(l-m)!})^{1/2}\,\mathrm{P}_l^m(-\frac{h_2(q)}{k_2})\,, \tag{3}$$

$$\psi_{\sigma ml}(\mathbf{r}) = \frac{\rho_1}{ik_2\rho_2}a_{\sigma ml}(\mathbf{r}). \tag{4}$$

In Eq. (2), k_1 and k_2 are the acoustic wavenumbers of the upper (water) and lower (sediment) halfspaces, $h_i(q)=\sqrt{k_i^2-q^2}$ are vertical wavenumbers, $\mathbf{r_s}=(\varsigma_s,\theta_s,\varphi_s)$ is the source position in spherical coordinates, $\mathbf{q}^{(\prime)}$ is a 2-dimensional transverse wave vector of length $q^{(\prime)}$ and azimuthal angle

$\varphi_{q^{(\cdot)}}$, $\varepsilon_m = \begin{pmatrix} 1, & m = 0 \\ 2, & m > 0 \end{pmatrix}$, κ is the ripple wave vector at the water-sediment interface, and $W_{12}(\mathbf{q},\mathbf{q'},\kappa)$ is the plane-wave transmission coefficient into the bottom. In Eq. (3), P_l^m is a Legendre function of order l and rank m.

Calculation of the a_n and $\psi_n(\mathbf{r})$ for a sinusoidal ripple is simplified by delta function correlations among the transverse wave vectors in the transmission coefficient [3, 4]; thus, eliminating one of the wave vector integrations. However, the remaining integration is still two-dimensional and requires significant computation time to complete using standard Gauss quadrature techniques. Methods to speed up these computations are being investigated, including the use of high-performance parallel computing facilities. Fast but approximate, more heuristic, techniques are also being tried to correct for the wave front effects by identifying and including contributions from optimal transmission paths into a rippled bottom based on the refraction formulas available from low-order perturbation theory. This approach has been implemented as an initial update in PCSWAT for sonar simulations of targets buried under ripple. The benchmark represented by Eqs. (1)-(4) is being used to validate these approximate corrections. In future work, it will also be available for comparison with FEM results.

WORK COMPLETED

In collaboration with J. Piper (NSWCPCD), E. I. Thorsos (APL-UW), and K. L. Williams (APL-UW), an analysis was carried out on observations of a buried sphere detected with a low-frequency (5-35 kHz) synthetic aperture sonar (SAS) at the SAX04 field measurement. The sphere was detected with good signal-to-noise ratios (SNRs) at both above and below the critical grazing angle. A corresponding set of high-frequency (165-195 kHz) SAS data was collected simultaneously with the low-frequency data. In Fig. 1, an image processed from the high-frequency data and centered on the sphere position is shown, indicating the sphere was fully buried under a ripple field of about 44 cm wavelength and with crests oriented 29^o relative to the sonar path.

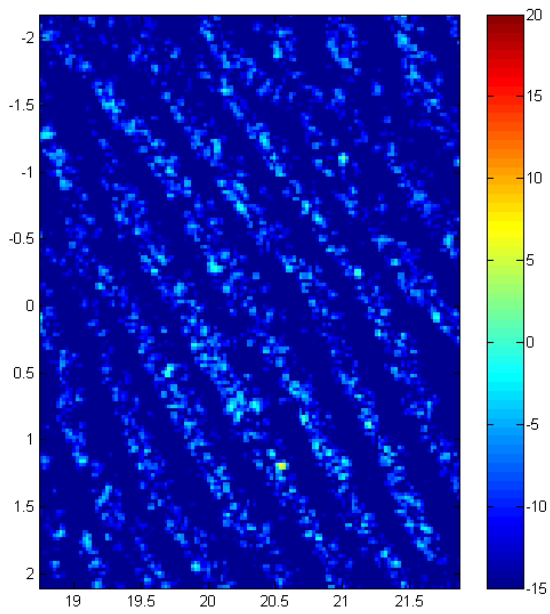

Figure 1. High frequency image of ripple field over buried sphere from run 1749. Image intensity is shown on a dB scale with arbitrary reference.

Since the SAX04 measurement included environmental support for acoustic parameters, the sphere backscatter measurements were controlled well enough to allow model validation at low and high grazing angles and over a band of ripple orientation angles and frequencies encompassing the region of ripple-induced backscatter enhancement predicted by perturbation theory. Results of this analysis were documented in a paper accepted for publication in the IEEE Journal of Oceanic Engineering [5].

The existing spheroidal-basis T-matrix code continued to be exercised for comparison with predictions of PCSWAT and with laboratory data collected with a buried 2 ft aluminum (Al) cylinder in NSWCPCD's freshwater pond facility. Of particular interest was assessing the impact of a new set of pond bottom parameters measured by APL-UW. These measurements showed that, at least over the last two years, the sediment sound speed in the NSWCPCD pond had risen and its corresponding attenuation had fallen significantly relative to previous measurements. Whether these changes were due to changes in the sediment or inaccurate measurements in the past is unknown but the new sediment sound speed does give rise to a faster roll-off of backscatter level with frequency from the 2 ft Al cylinder than measurements showed. This discrepancy is currently hypothesized to result from a failure of incident plane wave and far-field detection assumptions used to speed up model predictions. Verification of this hypothesis is contingent on updated models and is a current emphasis.

Updates to existing T-matrix scattering codes to remove far-field assumptions have been written and debugged for spherical targets. In these, the incident field can be configured to come from a phase-steered vertical line source of any length placed anywhere in a water halfspace. These updates form the basis for benchmarking future modifications and extensions. Unfortunately, the current set of codes currently require significant time to complete for a reasonable number of spectral points over the experimental measurement band, making it difficult to run comprehensive studies. A few modifications to improve computation speed are still being implemented but the greatest improvement is likely to come from porting the existing routines over to a computer facility with parallel processing capability. An Air Force High Performance Computing supercomputer account was obtained for this purpose and the process of modifying the codes to utilize parallel processing is ongoing.

RESULTS

Validation of ripple-induced transmission with SAX04 data: Using environmental data measured during SAX04 and sphere depth estimates deduced from BOSS imagery provided by Florida Atlantic University as inputs, comparisons with T-matrix backscatter predictions were carried out. The raw data for the below-critical-grazing angle detection shows that the acoustic penetration is skewed by the 29° offset of the surface ripple field relative to the sonar path. This observed skew was shown to be in agreement with T-matrix calculations. Additionally, measured SNRs over different frequency bands were compared to predictions made using both first and second-order perturbation theory for ripple diffraction. Figure 2 shows this comparison. Several runs of the low-frequency SAS are represented in four different panels because the various runs were carried out at different enough observation angles past the buried sphere to require separate backscatter calculations to properly match the data. A 2^{nd}-order perturbation T-matrix prediction for the backscatter SNR, assuming 3.8 cm burial depth (to the top of the sphere) and 1.78 cm ripple rms height, is given by the dashed line. Two solid lines, representing 1^{st}-order sonar equation predictions, bound the T-matrix result to present an approximate modeling error range due to uncertainty in the burial depth and ripple height estimates, which were expected to have the greatest error. The modeling error range was defined by setting burial depth = 2.7 cm, ripple rms height = 2.13 cm for the top solid line and burial depth = 4.9 cm, ripple rms height = 1.43 cm for the bottom solid line. The plotted experimental data points were obtained by filtering the

recorded backscatter signals in 10 kHz bands centered at 10, 15, 20, 25 and 30 kHz. Both the data and the models indicate a peak detection region around 25 kHz for the environmental conditions present during the test. These results confirm that ripple diffraction can play a critical role in long range (subcritical angle) buried target detection and that models based on sinusoidal ripple represent actual ripple effects reasonably well even at a 29° ripple orientation angle.

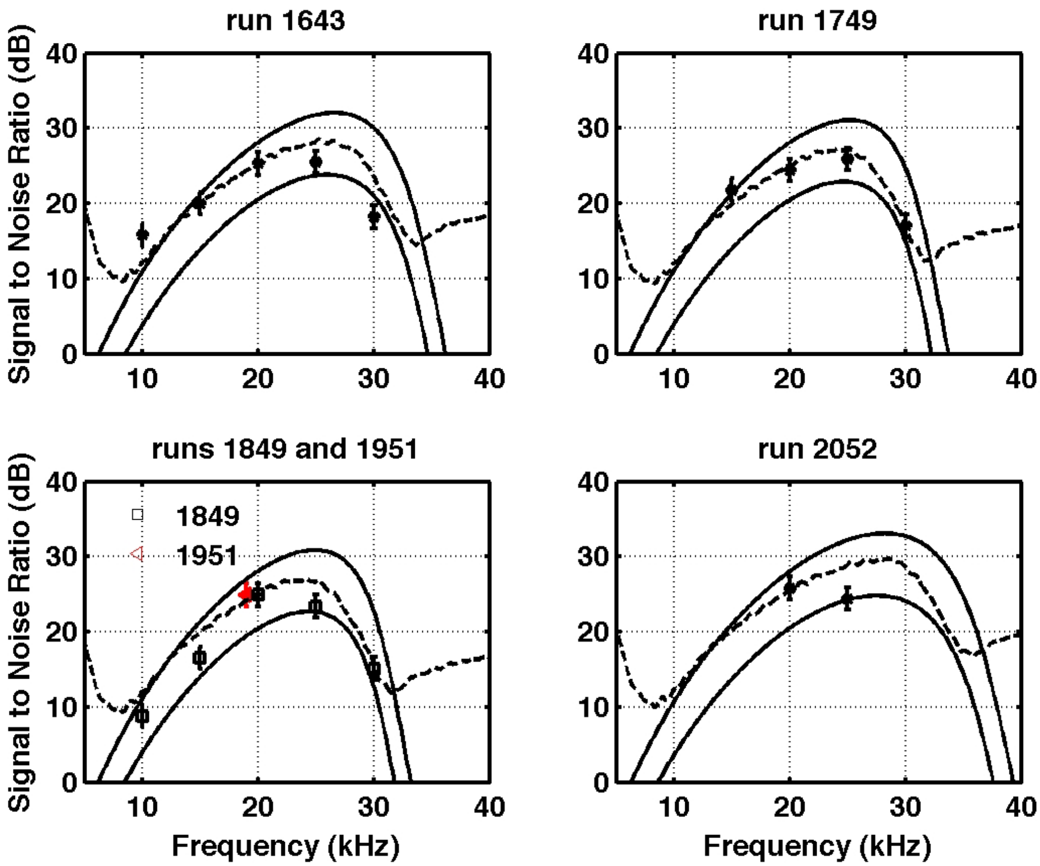

Figure 2. Model/data comparisons. The dashed black line is the T-matrix result for a sphere burial depth of 3.8 cm and ripple rms height of 1.78 cm. Solid black lines in each panel are sonar equation results that bound the modeling error range. Data were filtered in 10 kHz bands centered at 10, 15, 20, 25 and 30 kHz. The data point from run 1951 is offset slightly in frequency for clarity. Sonar equation results use 1st-order perturbation theory for penetration due to ripple, the T-matrix results use 2nd-order perturbation theory.

<u>T-matrix analyses:</u> Given updated pond bottom parameters from measurements performed by APL-UW in FY07 and FY08, the spheroidal T-matrix was used to recalculate the backscatter comparison with pond data collected in FY07 for a 2 ft Al cylinder buried under sinusoidal ripple in NSWCPCD's pond. The incident field is modeled as a plane wave propagating at a 20° grazing angle towards the target. All source/receiver/target positions and ripple parameters used were as reported in the FY07 ONR annual report. The result is shown in Fig. 3, where model results are smoothed over a 5 kHz moving window to facilitate comparison with the measurement points. The red line uses the updated sediment sound speed (1699.7,-7.0934) m/s while the blue line uses a value from less precise past measurements. Model results are terminated after about 33 kHz due to instability of the T-matrix

beyond that frequency. Despite the lower attenuation in the most recent sediment speed, the backscatter intensity is seen to roll off faster with frequency. This is caused by the higher value of the real part of the sound speed since a higher value causes the 1st-order field transmitted through the ripple to go evanescent at lower frequency. As mentioned above, it is believed that the resulting disagreement with the measurement points is caused by curved wavefront effects ignored in the far-field approximations used in the models to speed up calculations. Without these approximations, higher grazing-angle components of the incident field not accounted for in a plane wave can transmit through the ripple and, perhaps, restore the agreement with measured levels.

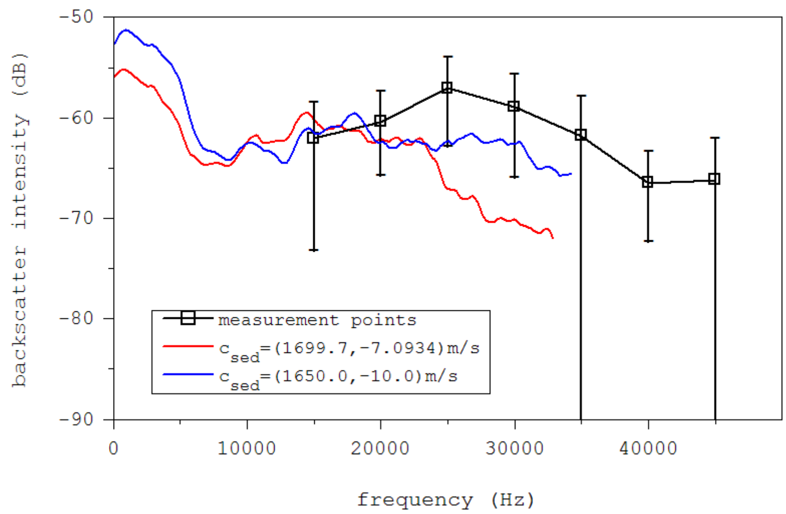

Figure 3. Model/data backscatter comparison for a 2 ft Al cylinder buried 11 cm under 75 cm wavelength, 2.46 cm amplitude sinusoidal ripple, with crests oriented 11° off from the rail direction. 2nd order perturbation theory is used in the model calculations.

An initial analysis to account for curved wavefront effects in backscatter calculations was performed based on an implementation of Eqs. (1)-(4) in existing spherical-basis T matrix scattering solutions. In Fig. 4, a comparison of model results is given assuming a point source and receiver placed 10.7 m slant range from a 14", oil-filled, steel spherical shell buried 5 cm under 75 cm wavelength, 2.4 cm amplitude sinusoidal ripple. The line from the source to the sphere is 20° from horizontal. The density and sound speed of the water and sediment are 1.0 and 2.0 g/cm^3, respectively, and 1482 m/s and (1699.7,-7.0934) m/s, respectively. Ripple transmission is determined with 1st-order perturbation theory. The black line represents the usual backscatter intensity when the incident field is a plane wave and far-field basis functions are used to expand the scattered field. The red line presents the new benchmark, which accounts for the wavefront curvature due to spherically spreading source and scattered fields. Both of these curves are smoothed over a 5 kHz moving window to approximate what would be deduced from processed SAS pond data. Thus, backscatter levels deduced from PCSWAT-simulated pond imagery are also plotted for comparison as circles. These PCSWAT results include a modification to account for transmission of higher grazing angle components of a bounded beam after the 1st-order field becomes evanescent. Compared to the incident plane wave result (black line), the point source benchmark (red line) clearly exhibits a much slower frequency roll-off in the backscatter intensity after the 1st-order field becomes evanescent. However, the PCSWAT results exhibit an even slower decay and the peak of the backscatter appears shifted to higher frequency. The resolution of this discrepancy is under investigation.

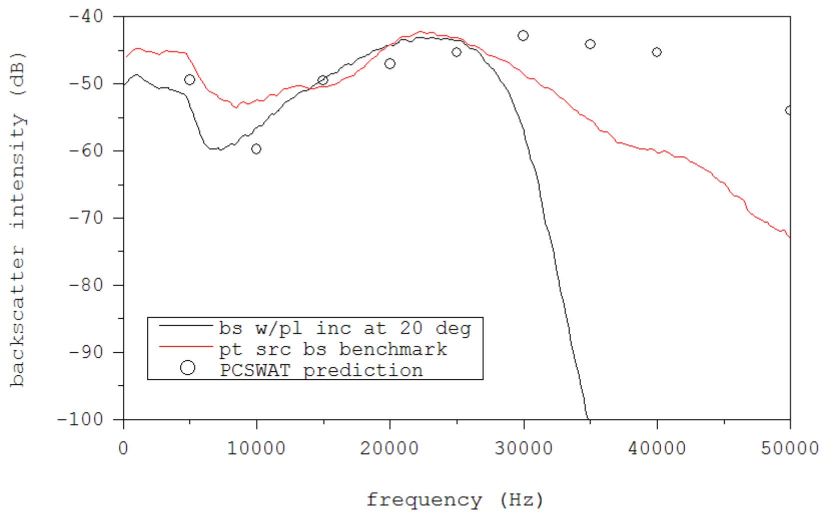

Figure 4. A comparison of 1st-order backscatter levels produced by a T-matrix solution using far-field approximations, a benchmark T-matrix solution allowing a point source and receiver near the target, and PCSWAT with modifications to approximate curved wavefront effects.

IMPACT/APPLICATIONS

This research extends our understanding of how sound penetrates a rough ocean bottom and interacts with buried targets, especially at shallow grazing angles. This will lead to improved sonar systems that can detect and identify targets buried over extended ranges in littoral environments.

TRANSITIONS

These results are being used to predict signal-to-noise levels in tests carried out this year and next year with support from ONR's Buried Mine Program (POC: R. Manning) and to update NSWCPCD's PC compatible Shallow Water Acoustic Toolset (PCSWAT) with support from SERDP's Munitions Management Program (POC: Herb Nelson) and ONR's Buried Mine Program.

RELATED PROJECTS

The present research is closely coordinated with theoretical and experimental efforts ongoing at APL-UW (E. Thorsos and K. Williams) and at NSWCPCD (J. Lopes, D. Burnett) under support from ONR Codes 321OA, 321OE, 321MS, and SERDP to resolve bottom target (mines and UXO) detection issues. D. Burnett is developing a numerical approach based on finite elements to model acoustic scattering and radiation by complex three-dimensional objects near boundaries. The work reported here will play an important role in verifying the resulting models. G. Sammelmann (NSWCPC) is also continuing to update PCSWAT with algorithms to account for buried targets under support from SERDP. Related efforts also exist elsewhere. H. Schmidt (Massachusetts Institute of Technology) and coworkers use modifications of the OASES program to predict multi-static scattering by proud and buried targets. This has undoubtedly been used to help interpret data collected at field tests performed in collaboration with the NATO Undersea Research Centre (NURC) research facility such as GOATS 98. J. Fawcett (DRDC-Atlantic, Canada) is using a variety of techniques to develop models of target scattering in layered ocean environments. Other researchers at NURC (A. Tesei, M. Zampolli, Finn

Jensen, et al.) are also testing acoustic propagation and scattering models by comparing predictions with data from buried targets and with other benchmark calculations provided at acoustic computation workshops hosted by NURC.

REFERENCES

[1] A. Boström, "Scattering of acoustic waves by a layered elastic obstacle in a fluid - An improved null field approach," *J. Acoust. Soc. Am.* **76**, 588-593 (1984).

[2] R. Lim, K. L. Williams, and E. I. Thorsos, "Acoustic scattering by a three-dimensional elastic object near a rough surface," *J. Acoust. Soc. Am.* **107**, 1246-1262 (2000).

[3] R. Lim and G. S. Sammelmann, "Subcritical Detection of Targets Buried Under a Rippled Interface: Extended Perturbation Theory," *Proceedings of Oceans '04 MTS/IEEE Techno-Ocean '04*, Kobe, Japan, pp. 1953-1961, November 2004.

[4] G. S. Sammelmann, "*Higher Order Perturbation Theory and Sediment Penetration in the Presence of Ripples*," submitted to *J. Acoust. Soc. Am*.

[5] J. E. Piper, R. Lim, E. I. Thorsos, K. L. Williams, "Buried Sphere Detection Using a Synthetic Aperture Sonar," accepted for publication in the IEEE J. Oceanic Eng.

PUBLICATIONS

J. E. Piper, R. Lim, E. I. Thorsos, K. L. Williams, "Buried Sphere Detection Using a Synthetic Aperture Sonar," accepted for publication in the IEEE J. Oceanic Eng. [refereed]

HONORS/AWARDS/PRIZES

The PI presented two invited papers at the 155th Meeting of the Acoustical Society of America in Paris, France, June 29-July 4, 2008. These were:

- J. Lopes, R. Lim, C. Dowdy, K. L. Williams, and E. Thorsos, "Sonar detection of targets buried under seafloor ripple at shallow grazing angles," J. Acoust. Soc. Am. **123**(5), pt. 2, 3755 (2008).

- R. Lim and G. S. Sammelmann, "Modeling bottom penetration for buried target detection," J. Acoust. Soc. Am. **123**(5), pt. 2, 3944 (2008).

The PI was also a co-author on another invited paper presented by K. Williams (APL-UW) at the Paris meeting:

- K. Williams, E. Thorsos, S. Kargl, J. Lopes, R. Lim, and C. Dowdy, "Measurement and modeling of targets deployed on and within sand sediments," J. Acoust. Soc. Am. **123**(5), pt. 2, 3943 (2008).